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Research Note

Urban stormwater management based on an analysis of climate change: A case study of the Hebei and Guangdong provinces

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ABSTRACT

Analysis of the urban climate changing is the basis for the implementation of stormwater management measures. This study analyzed the climate conditions of 230 cities in the Hebei and Guangdong provinces from 1958 to 2016, and then discussed stormwater management of these cities. The results demonstrated the following: (1) The climatic indicators differed significantly between the two provinces. These indicators include the aridity index, annual average potential evapotranspiration, precipitation, temperature, extreme precipitation frequency, precipitation intensity, drought frequency, and drought intensity of 146 cities in Hebei and 84 cities in Guangdong. (2) With the exception of temperature and potential evapotranspiration, most of the above indicators showed a non-significant trend (at the significance level of 5%) in the past 59 years. Temperature of most cities in the two provinces had a significant upward trend, and the potential evapotranspiration of most cities had a significant downward trend. (3) According to the above analysis, we constructed a system to evaluate the flooding and drought risk for these cities, and the evaluation indicated that all cities of Guangdong had a high flooding risk and approximately one-fifth cities of Hebei had a high drought risk. Finally, we divided 230 cities into five types based on the above risk analysis, and proposed stormwater management strategies for each type of city based on Low Impact Development (LID).

1. Introduction

Rapid progress of urbanization often causes environmental deterioration and ecological destruction in urban areas (Chen, Samuelson, & Tong, 2016; Cohen, 2006). In a number of cities, the urban impervious surface leads to water shortages and water pollution in drainage areas (DeLaria, 2008). Many cities are facing serious hydrological and ecological problems with the rapid urbanization in China, leading to nationwide property damage, heavy casualties, traffic paralysis, water pollution and economic losses (Li, 2012). The cities of Wuhan, Guangzhou and Beijing are typical cases, with frequent flooding and drought events occurring in recent years (Sheng & Nawari, 2016; Zhang, Yang, Voinov, & Gao, 2016). Hydrological and ecological protection have been bottlenecked for urban sustainable development in many developing countries (Han et al., 2016; Hubacek, Guan, Barrett, & Wiedmann, 2009; Li et al., 2016). In recent years, due to the severe global climate change, the economic losses caused by natural disasters, especially the flooding and drought events are gradually increasing. At the same time, more and more population and economy are gradually exposed to natural hazard because of the acceleration of urbanization (Güneralp, İnci, & Liu, 2015). Therefore, the assessment of urban flooding and drought risk is particularly important in urban reconstruction.

The conventional approaches to urban stormwater management overemphasize the drainage efficiency. However, these measures changed the natural hydrologic processes and led to further increases of storm frequency, magnitude, volume and decay time, and a decrease of base flow (Burns, Fletcher, Walsh, Ladson, & Hatt, 2012). Since the 1970s, in an attempt to control the negative influence of urbanization on hydrology and improve the ecological environment around the city, many stormwater management measures have been proposed. These measures include the Best Management Practices (BMPs, proposed by United States in 1972); Low Impact Development (LID, termed by United States in 1990); Sustainable Urban Drainage Systems (SUDS, a British drainage strategy launched in 1999); Water Sensitive Urban Design (WSUD, an urban water recycle system in Australia); and the Active Beautiful Clean Waters Program (ABC Waters Program, launched in 2006 by Singapore government). These measures have matured after decades of exploration and practice, and have been applied in many countries (Ahiablame, Engel, & Chaubey, 2012; Selvakumar,

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Muthukrishnan, Madge, Field, & Tafuri 2005; Andoh & Iwugo, 2002; Roy et al., 2008; Lim & Lu, 2016). Throughout the urbanization process, the Chinese government has made a great effort to solve urban droughts and floods. In 2012, based on the LID method and the stormwater management experiences of other countries, China proposed the idea of a “sponge city”. Sponge city means that the city can absorb, impound, leak, and purify rainwater with good “elastic” in adaptation to environmental change and disaster response like a sponge, and the stored water can be released and utilized when necessary (Yang, Scheffran, Qin, & You, 2015). Presently, sponge cities have risen to the national strategic level, and there were 30 cities received the government's financial support to pilot their own sponge cities by the end of 2016.

So far, there has been considerable research on urban stormwater management in China (Jia, Yao, & Yu, 2013; Liao, Zhang, Wu, He, & Chen, 2015; Yu, Huang, & Wu, 2014). However, few studies have taken into account the background of climate change. The global climate is changing significantly, and the warming of the climate is bringing more energy into the atmospheric system, resulting in a more vigorous hydrological cycle (Güneralp et al., 2015). On the other hand, the change of land use and land cover make the regional hydrologic process more complex and varied (Zhang et al., 2004; Zhang, Lu, Jing, Rustomji, & Hairsine, 2008). The extreme weather events have become more frequent in many regions, including northwest China, northern Europe, the southern US, southeast Asia and others (Cheng et al., 2015; Khoi & Trang, 2016; Rajczak, Pall, & Schär, 2013; Wang & Zhang, 2008). The extreme changes in climate will force many cities to face the serious risks involved with flooding and drought, which will result in a significant economic burden (Lo, Xu, Chan, & Su, 2015; Xie, Lo, Zheng, Pan, & Luo, 2014).

Hebei and Guangdong Provinces were selected as examples of a typical arid and semi-arid and a humid and semi-humid region, respectively. What is the interaction of urban climate change and stormwater management? What are the differences of urban climate change and stormwater management in Hebei and Guangdong? The above two problems deserve further study, therefore, the main goals of this study were (1) to analyze the climate characteristics and changes in the cities of Hebei and Guangdong over the past 59 years (1958–2016), (2) to construct a system to evaluate the flooding and drought risks based on meteorological factors, and (3) to discuss the stormwater management for these cities based on the above analysis. The results from this study will provide critical references for the development of sponge cities worldwide.

2. Materials and methods

2.1. Study area

The Hebei Province (36°05′N- 42° 40′N, 113°27′E- 119° 50′E, Fig. 1b) is divided into 11 prefecture-level cities (including 22 county-level cities and 113 counties and autonomous counties), and has an area of 199,000 km^2 and a population of 74.7 million (2016). The climate of Hebei is a temperate, continental, and monsoonal, with a mean annual precipitation of approximately 500 mm, and a mean annual temperature of 10 °C. Hebei has begun to build its own “sponge city”, where all the new and developing projects must meet the requirements of sponge city. Qian’an County has been selected as a national sponge city pilot in 2015.

The Guangdong Province (20°13′N-25°31′N, 109°39′E-117°19′E, Fig. 1c) is located in southern China, has a population of 108 million and an area of 179,800 km^2, and is divided into 21 prefecture-level cities (including 23 county-level cities and 40 counties and autonomous counties). The climate of Guangdong is subtropical and monsoonal with a mean annual precipitation of approximately 1777 mm and a mean annual temperature of 22 °C. Zhuhai and Shenzhen have been selected as national sponge city pilots in 2016.

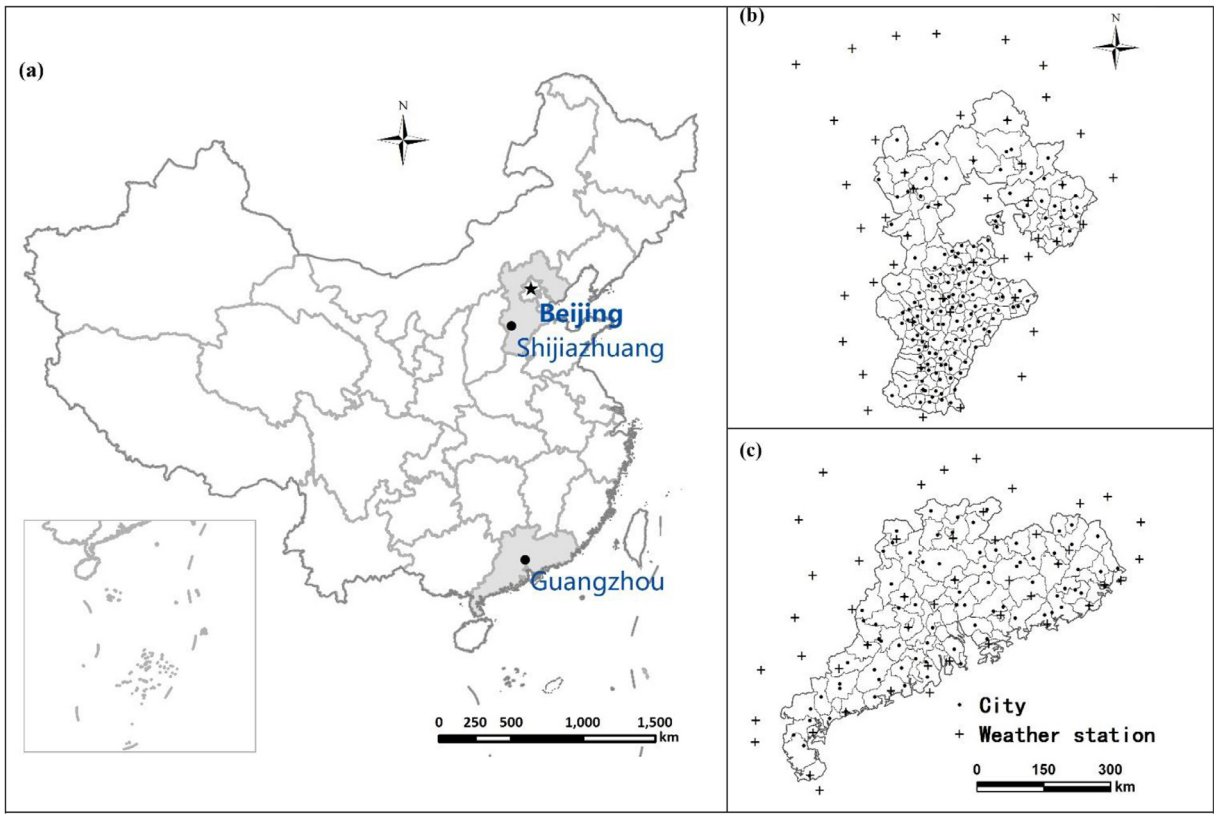

Fig. 1. Geographical locations of Hebei and Guangdong in China (a), the locations of weather stations and cities in Hebei (b), and in Guangdong (c).

2.2. Data collection and pre-processing

The meteorological data for 1958–2016, including daily average (maximum and minimum) temperature, precipitation, wind speed, sunshine duration, atmospheric pressure, and relative humidity, were obtained from 93 national weather stations (Fig. 1) (http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0.html). In previous studies, extreme precipitation was considered as a value of precipitation exceeding a certain threshold. The threshold was typically defined by the use of a percentile method (Groisman et al., 1999). Based on the cumulative probability distribution function (CDF), the 95% quantile was used as the threshold value, and the standard time period, 1971–2000, was recommended by the World Meteorological Organization (WMO). The daily precipitation value exceeding this threshold was defined as the extreme precipitation (EP) event, that is, the occurrence probability of extreme precipitation events in the standard time period was 5%. The extreme drought event (ED) was defined using the same method, which is referring to consecutive dry days (CDD), proposed by Frich et al. (2002).

2.3. Mann-Kendall (MK) trend test

The Mann–Kendall statistical test (Kendall, 1975; Mann, 1945), also called the MK test or Kendall's tau test, is a rank-based non-parametric test, widely used to assess the significance of trends in a hydro-meteorological time series, such as streamflow, temperature, and precipitation (Yue, Pilon, & Cavadias, 2002). The null hypothesis of this test is that a sample of data $\{x_i, i = 1,2,3,\ldots,n\}$is independent and identically distributed. The alternative hypothesis is that the series has a monotonic trend. The statistic S is defined as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{1}$$

where x_i and x_j are the sequential data values in time series i and j respectively, n is the length of the set, and $\mathrm{sgn}(x_j - x_i)$ is the sign function, defined as:

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} 1, & if\ x_j > x_i \\ 0, & if\ x_j = x_i \\ -1, & if\ x_j < x_i \end{cases} \tag{2}$$

Mann (1945) and Kendall (1975) have documented that when $n > 8$, the statistic S is approximately normally distributed with the mean E(S) and the variance Var(S) as follows:

$$E(S) = 0 \tag{3}$$

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{m=1}^{n} t_m m(m-1)(2m+5)}{18} \tag{4}$$

where t_m is the number of ties of extent m.

The standardized test statistic Z was then calculated by

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}}, & if\ S > 0 \\ 0, & if\ S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}}, & if\ S < 0 \end{cases} \tag{5}$$

The standardized MK statistic, Z, follows the standard normal distribution with a mean of zero and a variance of one. For the test, the positive values of Z indicate increasing trends, while a negative Z value shows decreasing trends.

2.4. Potential evapotranspiration and aridity index

Potential evapotranspiration (ET_p, mm) was calculated using the Penman formula (Brutsaert, 2005; Penman, 1948):

$$ET_p = \frac{\Delta}{\Delta + \gamma}\frac{R_n}{\lambda} + \frac{\gamma}{\Delta + \gamma}E_A \tag{6}$$

$$E_A = f(u_2)(e_s - e_a) \tag{7}$$

$$f(u_2) = 0.26(1 + 0.54u_2) \tag{8}$$

where Δ is the slope of the vapor pressure curve versus temperature ($kPa \cdot {}^{\circ}C^{-1}$), R_n represents the net radiation at the reference surface ($MJ \cdot m^{-2} \cdot d^{-1}$), γ represents the psychrometric constant ($kPa \cdot {}^{\circ}C^{-1}$), is the latent heat of vaporization ($MJ \cdot kg^{-1}$), E_A is the drying power of the air, u_2 represents the wind speed at 2 m height ($m \cdot s^{-1}$), e_s is the saturated vapor pressure (kPa), and e_a represents the actual vapor pressure (kPa). A complete set of equations is proposed by Allen, Pereira, Raes, and Smith (1998) to compute the parameters of the above three equations according to the available weather data.

The annual aridity index (AI, dimensionless) is represented as the total annual potential evapotranspiration to annual precipitation ratio (Budyko, 1974; Meng, Ni, & Zhang, 2004) and is defined as follows:

$$AI = \frac{AET_p}{AP} \tag{9}$$

where AET_p is the annual potential evapotranspiration (mm) and AP is the annual precipitation (mm). The climatic regimes, such as hyper-humid, humid, sub-humid, semi-arid, arid and hyper-arid are defined by the AI range of $0.1875 \le AI < 0.375$, $0.375 \le AI < 0.75$, $0.75 \le AI < 2$, $2 \le AI < 5$, $5 \le AI < 12$, and $12 \le AI < 30$, respectively (Arora, 2002; Ponce, Pandey, & Ercan, 2000).

2.5. Assessment system of urban flooding and drought risk

Mathematical and statistical methods is often used in flooding and drought risk assessment (Zhang & Zhou, 2015; Dang, Babel, & Luong, 2011; Nayak, Sudheer, & Ramasastri, 2005). In this study, the fuzzy comprehensive evaluation method was used to evaluate the degree of threat from flooding and drought in the 230 cities of Hebei and Guangdong provinces, because this method can better measure the vagueness or information of uncertainties in qualitative analysis.

The mean value of climate index reflects the local climate condition under normal conditions, and the trend of climate index statistically reflects the climate level in the future. Therefore, the annual average of AI, EPF, EPI, EDF, EDI and their trend were selected to reflect the challenges of stormwater management in urban areas from two aspects of conventional and extreme climate conditions. In this study, the trend result of these indicators has five categories, i.e. significantly increasing trend, non-significant upward trend, non-significant trend, non-significant downward trend, significantly decreasing trend. The risk indexes, i.e. IAI, IEPF, IEPI, IEDF, IEDI were defined as the weight of the above five trends indicators with values of {1.2, 1.1, 1.0, 0.9, 0.8} multiplying the corresponding average value of AI, EPF, EPI, EDF, and EDI. Among these indexes, IAI represented the degree of wet and dry in the conventional climate; IEPF and IEPI reflected the severity of urban flooding problems caused by extreme precipitation events; and IEDF and IEDI reflected the probability and intensity of the risk of urban extreme drought. Typical triangle function were selected as the membership function, and the judgment set was identified as {v1, v2, v3, v4}, which represented four risk levels (from low to high). The typical evaluation results were represented by a row vector with four indicator, i.e., $\{u_{i1},u_{i2},u_{i3},u_{i4}, i = 1,2,3,\ldots,230, u_{i1} + u_{i2} + u_{i3} + u_{i4} = 1\}$ in which the value of u_{ij} (j = 1, 2, 3, 4) represented the membership degree of the i-th city to the j-th judgment, and the higher membership degree meant a higher subordination to the corresponding judgment. Because the membership vector cannot distinguish the evaluation object well, the usual solution is to provide each indicator of a judgment set a standard score, typically {1, 3, 5, 7}. A matrix product of judgment vector and score set represents the final evaluation results, and the results were

defined as a risk index (RI) in this study. The IAI, IEPF and IEPI were used to evaluate the risk of flooding. The IAI, IEDF, and IEDI were used to evaluate the risk of drought according to the implication of each climatic indicator. Because there is no significant difference in the importance of each index, we used the same weights for each indicator.

2.6. Summary of the LID strategy

LID is a common strategy for the international community of urban water environmental protection and the sustainable development of stormwater management, which includes engineering and non-engineering measures. The former refers to the relevant laws, policies and the supervision and management mechanisms, and the latter includes bio-retention facilities, permeable pavement, green roofs, low elevation greenbelt. Specifically, (1) The bio-retention facilities were built mainly in parking lots, along roads, or in residential areas, employing small area depressions below ground for planting native plants with mulch cover. These facilities can reduce runoff, intercept pollutants, recharge groundwater and promote infiltration and evaporation. The bio-retention facilities can reduce 50%-97% of the runoff volume with an effective purification effect (Brown & Hunt, 2008; Debusk & Wynn, 2011). (2) Permeable pavement was usually used to replace the traditional hardened road surface with grid brick, pervious asphalt, pervious cement, vegetation or filling the pores with sand. It was used mostly on roads with inconvenient drainage or small traffic flow, to temporarily store runoff, alleviate road-area water and accelerate the infiltration of rainwater into the soil. Different types of permeable pavement had different rainwater retention and pollutant removal rates. The average runoff reduction rate of permeable pavement was 50%–93%, and its suspended substance and heavy metal removal rate was 75%–99% (Rushton, 2001; Myers, Beecham, & Leeuwen, 2011). (3) A green roof is a drainage system made up of vegetation, substrate, filter layer, and drainage material on the roof of a building. It can reduce runoff, utilize rainwater and save energy with runoff retention rate of 19%-100% and a runoff peak delay of approximately 2 h (Berndtsson, 2010; Denardo, Jarrett, Manbeck, Beattie, & Berghage, 2005). (4) A sunken green space refers to a green space that is below the surrounding hardened ground surface by 5–25 cm. Green spaces can collect rainfall runoff, slow urban flooding and supplement the groundwater because the overflow mouth is higher than the green land and is below ground level. Conversely, the sunken green space is better able to address runoff pollutants, exhibiting a reduction rate of approximately 50% COD, NH_4^+-N, TP (Cheng, Yang, Huang, Xie, & Li, 2009). The main stormwater management techniques of LID were described in Table 1, which referred to Center For Watershed Protection and other literatures (Beijing University of Civil Engineering and Architecture, 2015; Eckart, Mcphee, & Bolisetti, 2017; Brown & Hunt, 2008; Debusk & Wynn, 2011; Rushton, 2001; Myers et al., 2011; Berndtsson, 2010; Denardo et al., 2005).

3. Results

3.1. Characteristics of climatic indicators in the cities of Hebei and Guangdong

The characteristics of climatic indicators differed significantly in the two provinces (Fig. 2). The annual average AI values of Hebei were from 1.37 to 2.50. Among the 146 cities of Hebei, 112 cities (accounting for 76.7% of the provincial total) belong to the sub-humid area, which mainly distributed across the northeastern, central and southern part of Hebei, and 34 cities (23.3%) belong to the semi-arid area. Qinglong County had the minimum AI and Huailai County had the maximum value. The AI values of the 84 cities in Guangdong range from 0.57 to 1.05, and half of these cities belong to the humid area, which are mainly located in the central part of Guangdong, and other 42 cities (50.0%) belong to the sub-humid area. Fogang County had the minimum AI and Nan'ao County had the maximum value (Fig. 2a).

The annual average ET_p ranged from 775.3 mm (in Kangbao County) to 952.8 mm (in Jing County) in Hebei, which gradually reduced from southeast to northwest. ET_p ranged from 1095.8 mm (in Lianzhou City) to 1343.9 mm (in Xuwen County) in Guangdong with a similar spatial pattern to Hebei (Fig. 2b).

The annual average precipitation in Hebei ranged from 347.3 mm (in Kangbao County) to 696.3 mm (in Zunhua City) and decreased from west to east. The annual average temperature ranged from 2.8 °C (in Kangbao County) to 14.1 °C (in Jize County) and increased from north to south. The corresponding values ranged from 1384.3 mm (in Raoping County) to 2186.1 mm (in Yangdong County) and from 19.0 °C (in Lechang City) to 23.7 °C (in Xuwen County) in Guangdong, respectively. The heavy precipitation was mainly located around the Pearl River Delta, and the temperature of the southern region was higher than the northern region in Guangdong (Fig. 2c, d).

The annual average extreme precipitation frequency (EPF) ranged from 3.1 time (in Qing County) to 3.9 time (in Wanquan County) in Hebei and from 6.17 time (in Nan'ao County) to 8.26 time (in Lian'nan Yao Autonomous County) in Guangdong (Fig. 2e). The annual average extreme precipitation intensity (EPI) ranged from 27.8 mm (in Kangbao County) to 64.0 mm (in Leting County) in Hebei and from 60.4 mm (in Lechang City) to 98.9 mm (in Yangdong County) in Guangdong (Fig. 2f).

The annual average extreme drought frequency (EDF) ranged from 1.8 time (in Daming County) to 2.2 time (in Wanquan County) in Hebei.

Table 1
Summary of stormwater management techniques in LID.

LID practices	Main function						Suggested application scenario
	Interception	Purify	Rainwater reuse	Groundwater recharge	Reduction of runoff volume (%)	Reduction of suspended solids (%)	
Bio-retention	+ +	+ +	+	+ + +	50–97	70–95	W
Permeable pavement	+ +	+ +	+	+ + +	50–93	80–90	W/D
Green roof	+ +	+ +	+	+	19–100	70–80	W
Sunken green space	+ +	+ +	+	+ + +	N/A	N/A	W/D
Reservoir	+ + +	+ +	+ + +	+	N/A	80–90	D
Rainwater tank	+ +	+ +	+ + +	+	N/A	80–90	D
Stormwater treatment wetland	+ + +	+ + +	+	+ + +	N/A	50–80	W
Penetrating well	+ +	+ +	+	+ + +	N/A	N/A	W
Grassed swales	+	+ + +	+	+ +	N/A	35–90	W/D

Note: the number of the cross indicates the level of ability, "+" means weak, "+ +" means general, and "+ + +" means strong. Letters "W" and "D" on behalf of high risk of drought and waterlogging, respectively. "N/A" means no data.

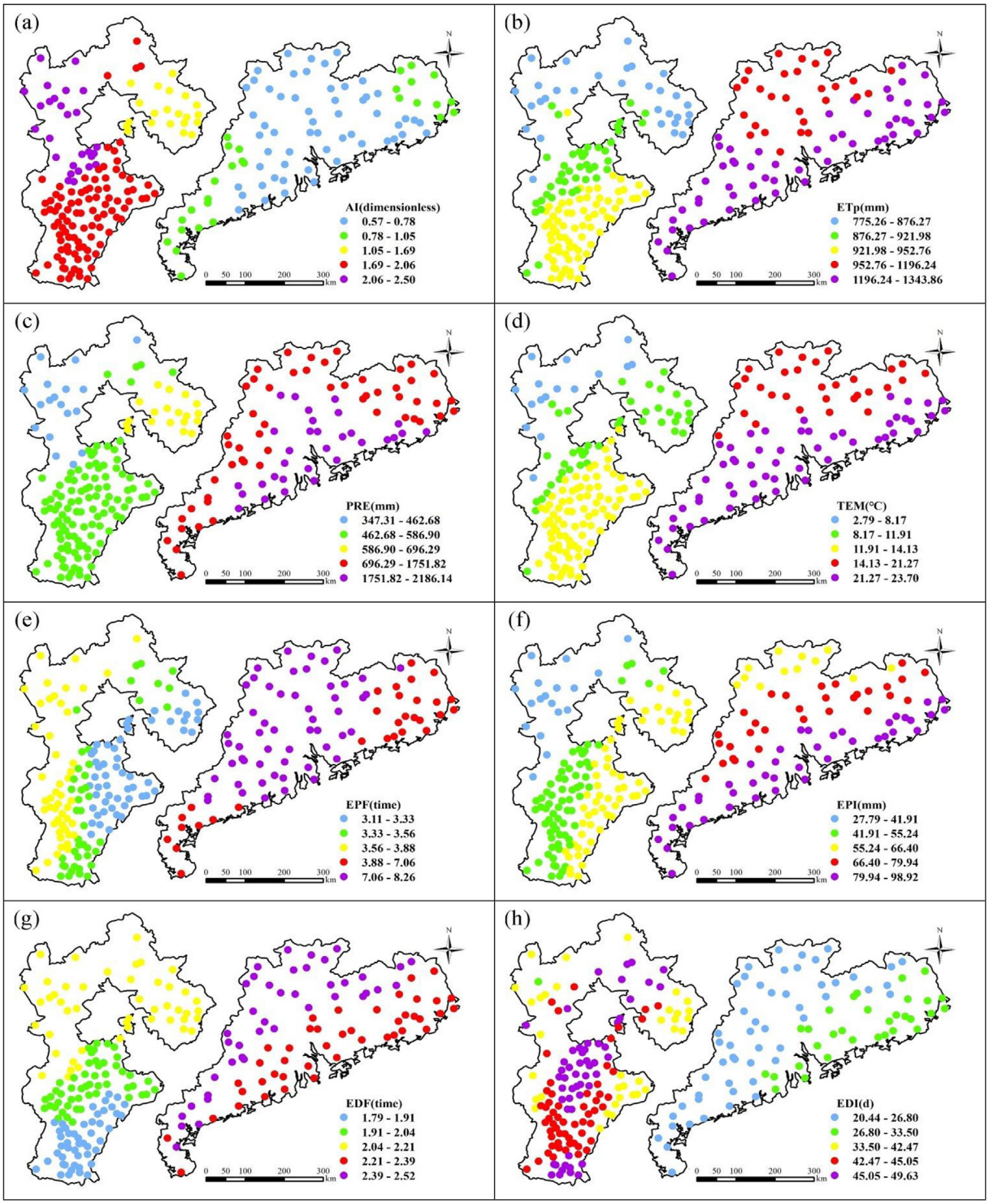

Fig. 2. The spatial distribution of climatic indicators in the cities of Hebei and Guangdong: the annual average (a) AI, (b) ET_p, (c) PRE, (d) TEM, (e) EPF, (f) EPI, (g) EDF and (h) EDI.

In Guangdong, the responding values ranged from 2.3 time (in Shenzhen City) to 2.5 time (in Lianshan Zhuang Autonomous County) (Fig. 2g). The annual average extreme drought intensity (EDI) in Hebei ranged from 33.5 d (in Zhangbei County) to 49.6 d (in Fengning Manchu Autonomous County), and the corresponding values in Guangdong ranged from 20.4 d (in Lechang City) to 31.2 d (in Nan'ao County) (Fig. 2h).

3.2. Trend of climate change in Hebei and Guangdong

The trend of climate change was analyzed by the MK trend test method with a 5% significance level. The AI of 53 cities (accounting for 36.3% of the provincial total) in Hebei showed an upward trend, 91 cities had a downward trend, and the other 2 counties (Qingyuan County and Guantao County) had no trend. In Guangdong, all the cities showed a downward trend, in which 37 cities showed significant

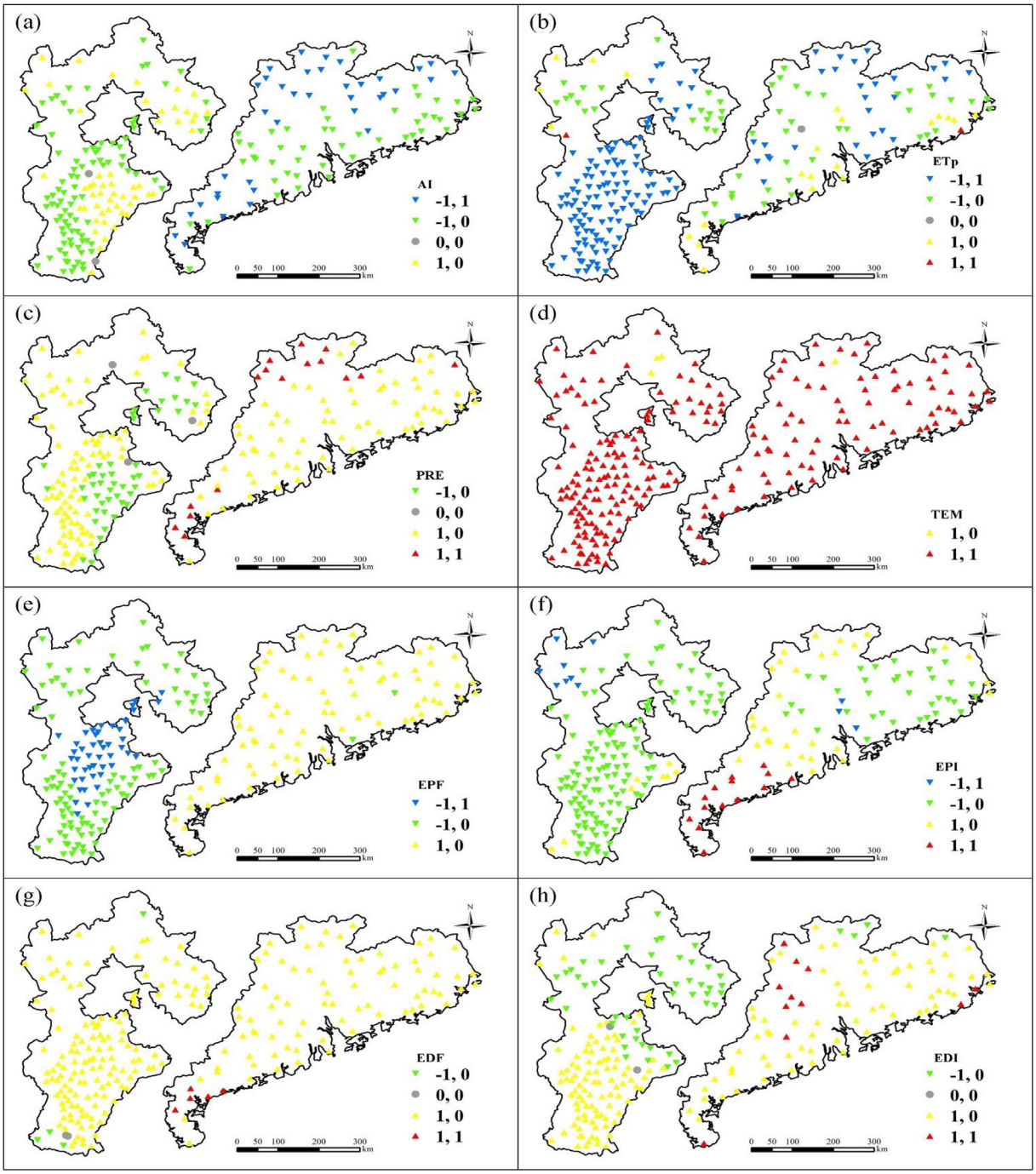

Fig. 3. Trend of climatic indicators in the cities of Hebei and Guangdong, (a) AI, (b) ET_p, (c) PRE, (d) TEM, (e) EPF, (f) EPI, (g) EDF and (h) EDI. In these figures, "−1,1" means a significant downward trend, "−1,0" means a non-significant downward trend, "0,0" means no trend, "1,0" means a non-significant upward trend, and "1,1" means a significant upward trend.

trends, and other cities showed a non-significant trend (Fig. 3a).

The ET_p in most cities showed a decrease trends (Fig. 3b). The ET_p of 120 cities (accounting for 82.2% of the provincial total) in Hebei showed a significantly decreasing trend. 20 cities had a non-significant declining trend, and only 5 cities had a non-significant upward trend and 1 city (in Wei County) had a significant upward trend. The ET_p of 65 cities (77.4%) in Guangdong showed decrease trends, in which 36 cities showed a non-significant and other 29 cities showed significant trends, and 18 cities (21.4%) had increase trends. Only Huilai County had significant increase trend, and only Sihui City had no trend (Fig. 3b).

The PRE of most cities in the two provinces showed a non-significant trend, among them, 48 cities (32.9%) showed a non-significant decreasing trend and 95 cities (65.1%) had a non-significant increasing trend, other 3 cities (Dacheng County, Luannan County and Fengning Manchu Autonomous County) had no trend in Hebei. The PRE of all cities in Guangdong Province had increasing trend, in which 16 cities (19.0%) showed significant trends (Fig. 3c). Except Longhua County, Chengde City, and Luanping County of Hebei and Shaoguan City of Guangdong had a non-significant increasing trend, the TEM of other cities in the two provinces had a significantly increasing trend (Fig. 3d).

The EPF of all the citiesin Hebei had downward trend (including 46 cities had significant trend and 100 cities had a non-significant trend)

and most cities (except Zijin County and Shenzhen City had a non-significant downward trend) in Guangdong had a non-significant upward trend (Fig. 3e). The EPI of 130 cities (89.0%) in Hebei showed a non-significant downward trend, and only 8 cities in the northwest showed significant downward trends and other 8 cities in southwest and southeast of Hebei showed non-significant upward trends. The situation is more complex in Guangdong, the number of cities with non-significant downward trends, significant downward trends, non-significant upward trends and significant upward trends were 36, 3, 31 and 14 respectively (Fig. 3f).

The EDF of most cities in the two provinces had a non-significant upward trend, only 4 cities in Hebei had a non-significant downward trend, 2 cities in Hebei had no trends, and 5 cities in Guangdong had significant upward trends (Fig. 3g). The EDI of 46 cities (31.5%) showed non-significant downward trends, 98 cities (68.1%) showed a non-significant upward trend, and only Dingxing Country and Botou City showed no trend in Hebei. Most cities (95.2%) in Guangdong showed upward trends, only Nanxiong City, Shixing County, Jiaoling County and Renhua County had non-significant downward trends (Fig. 3h).

3.3. Urban flooding and drought risk

With the use of fuzzy comprehensive evaluation method mentioned above, we have evaluated the urban flooding and drought in the 230 cities of the two provinces, and the results were shown in Fig. 4.

To distinguish the severity of flooding and drought risk, we divided the range of risk index into three levels (as shown in the legend of Fig. 4); i.e., the city has “low risk” when $1 \leq RI < 3$, “moderate risk” when $3 \leq RI < 5$, and “high risk” when $5 \leq RI \leq 7$. The flooding and drought risk of each city was shown in Fig. 4, and the number of cities involved in each risk level was shown in Table 2.

As shown in Fig. 4(a) and Table 2, there were 124 cities in Hebei (accounting for 84.9% of the provincial total) had low flooding risks and 22 cities had moderate flooding risks. Similarly, 28 cities in Hebei had high drought risks and 118 cities had moderate drought risks. Most cities in Guangdong (accounting for 63.1% of the provincial total) had low drought risks and other 31 cities had moderate drought risks, and all cities in Guangdong had high flooding risks.

3.4. Stormwater management strategies

According to the above analysis, we divided the 230 cities into five types (Table 3). The number of each type city was 96, 28, 22, 53, and 31, respectively. All the Type 1, Type 2, and Type 3 cities were located in Hebei, and all Type 4 and Type 5 cities were located in Guangdong (Fig. 5).

The urban precipitation in Guangdong province was more abundant, while most cities in Hebei were short of water and even had high drought risk level. This is consistent with the drought risk identification based on the two-year return period developed by Wu (Wu et al., 2018). Therefore, the cities in Hebei should pay attention to rainwater recycling and groundwater recharge, while cities in Guangdong should focus on source control of rainwater runoff and urban sewage. In

Table 2
Classification of flooding and drought risk.

Risk level		Low risk	Moderate risk	High risk
Range of RI		1–3	3–5	5–7
Number of cities with flooding risk	Hebei	124	22	0
	Guangdong	0	0	84
	Total	124	22	84
Number of cities with drought risk	Hebei	0	118	28
	Guangdong	53	31	0
	Total	53	149	28

Table 3
Five city types in the Hebei and Guangdong Provinces.

Types	Description	Number
Type 1	Low flooding risk and moderate drought risk	96
Type 2	Low flooding risk and high drought risk	28
Type 3	Moderate flooding risk and moderate drought risk	22
Type 4	High flooding risk and low drought risk	53
Type 5	High flooding risk and moderate drought risk	31
Total		230

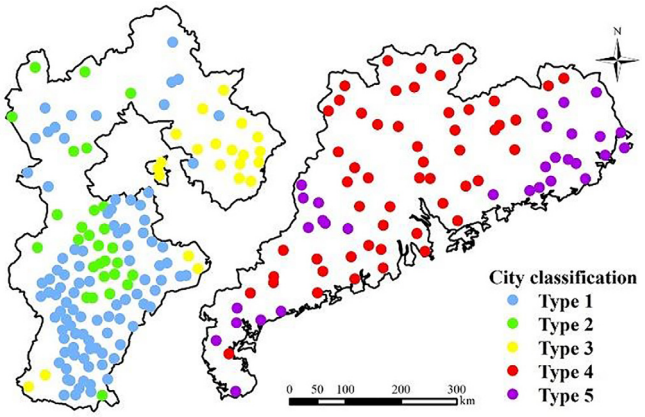

Fig. 5. The distribution of the five city types.

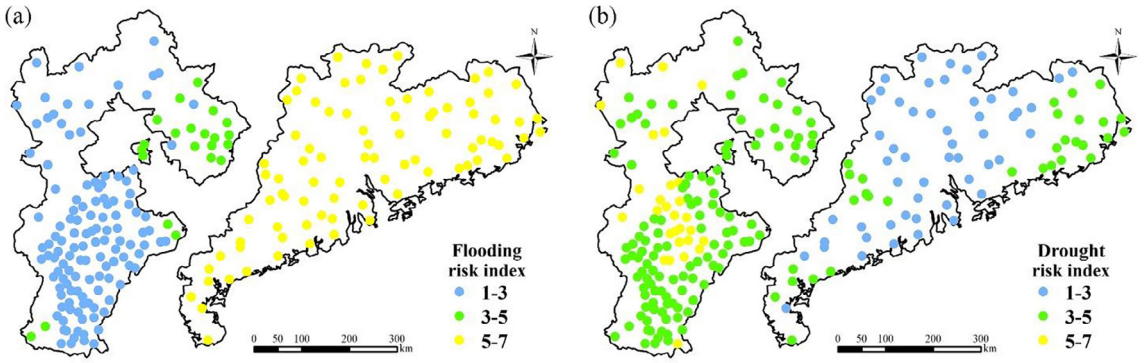

Fig. 4. Risk assessment results of 230 cities: (a) flooding risk and (b) drought risk.

Table 4
LID facilities suitable for the different types of city.

Urban type	LID practices
Type 1	Reservoir, Rainwater tank, Permeable pavement
Type 2	Reservoir, Rainwater tank, Sunken green space
Type 3	Permeable pavement, Grassed swales, Bio-retention, Penetrating well
Type 4	Bio-retention, Green roof, Sunken green space
Type 5	Bio-retention, Green roof, Stormwater treatment wetland

particular, we give the LID facilities that each type of city can adopt in the following (Table 4).

4. Discussions

4.1. Urban stormwater management in response to climate change

Based on the statistical analysis of climate indicators, the mean and trend were introduced into urban flooding and drought risk assessment. However, the impact of climate change on stormwater management is quite complex. (1) Climate change has significant impact on the hydrologic cycle, the change in rainfall, and evapotranspiration. Extreme weather events may have many negative effects on urban water systems, including water shortages, flooding, the uneven distribution of water resources and water pollution. In Southern China, the intensity of rainfall has increased significantly during the rainy season, although the total annual rainfall has changed very little from 1950 to 2009. The intensified rainfall does not improve soil moisture (due to the stationary soil water holding capacity), but the increase of dry days has decreased the soil moisture significantly. Therefore, climate change may lead to extreme hydrologic events, including droughts and flooding in this region (Zhou et al., 2011). (2) Climate change can deteriorate the water quality by affecting base flows, surface runoff and water temperature (Yang, Chan, & Scheffran, 2016). The decreasing base flows restricts the discharge of toxic substances. Heavy metals and organic pollutants will persist in soils and sediments, leading to water pollution, eutrophication and water temperature rise. The increase in surface runoff may lead to water body dysfunction, due to heavy rainfall washing nutrients, trash, sediments and other harmful materials into water bodies. Climate change directly increases the water temperature of rivers and lakes, enhancing the growth of algal blooms, affecting the levels of dissolved oxygen and destroying the balance of water in an ecological environment.

On the other hand, the hydrologic changes can affect the standards, scale of facilities in the construction of sponge cities, and these facilities need to adapt to the changes of rainfall intensity, flooding, and water pollution conditions. However, for lacking both guidelines and tools to assess the impact of climate change on hydrology, the interaction between climate change and stormwater management have not been thoroughly elucidated (Semadeni-Davies, Hernebring, Svensson, & Gustafsson, 2008; Ghazal, Ardeshir, & Rad, 2014; Yang et al., 2015), and the uncertainty of climate change will make stormwater management more complex (Saraswat, Kumar, & Mishra, 2016). The hydrologic cycle is also affected by the natural environment and the human-built environment (Semadeni-Davies, Hernebring, Svensson, & Gustafsson, 2008). Through changes in land use and greenhouse gas emissions, urbanization affected the urban temperature, which is considered to make floods and droughts more frequent and dangerous (Kalnay & Cai, 2003; Güneralp et al., 2015). Therefore, urban stormwater management should consider the effects of climate change, especially the extreme climate events.

4.2. Main uncertainties of this study

First, we used an annual time scale without seasonal or monthly scales in order to analyze the climate change. We ignored the fluctuation of the climate index over a yearlong period, which cannot reflect the year-on-year change of an indicator seasonally or in a particular month. Fortunately, the results are similar to many previous studies. Wang, Wen, Song, and Dou (2016) found that the AI was high in northern China with an increasing trend and low in southern China with a declining trend. Yin, Wu, and Dai (2010) and Yao, Zhao, Zhang, Jia, and Liu (2014) analyzed the temporal changes trend of potential evapotranspiration in the Hebei and Guangdong Provinces during the period of 1971–2008. Their results showed that the annual potential evapotranspiration was slightly smaller than our research, but had the same changing trend as ours. In addition, the trend of extreme precipitation and ETp in Guangdong (Yang et al., 2010; Thomas, 2015; Gao, Chen, Ren, Chen, & Liao, 2006) was similar to this study. Second, the traditional MK test method was applied to detect the climate trend, but this method cannot quantify this trend. If the initial data have a sequence correlation, the analysis result from the use of the MK method may be biased, as the method is based on the independence and randomness of the time series data (Yue et al., 2002; Hamed & Rao, 1998). Third, the frequency of extreme drought events in the cities of Guangdong province was relatively high by using a relative threshold method, which did not mean the drought risk of these cities was high because their intensity of the extreme drought events was low. Although there are some differences in the definitions and indicators of extreme events, many studies have shown the same trend of frequency (Zhai, Zhang, Wan, & Pan, 2005; Chen & Sun, 2017) and intensity (Ding et al., 2007; Chen & Sun, 2015; Wang, Zhu, Xu, & Liu, 2015). Finally, stormwater management is an important, comprehensive project for urban construction, which involved multidisciplinary knowledge and covering a number of departments. This study only analyzed this management from a climate perspective by use of LID.

5. Conclusions

This study analyzed the climate conditions of 230 cities in the Hebei and Guangdong provinces from 1958 to 2016, and primarily discussed the stormwater management practices for these cities. The climate characteristics of Hebei and Guangdong differed greatly. Hebei has lower temperatures, lower precipitation and a drier climate, compared with Guangdong. All the cities in the two provinces had a significant warming trend, but cities in Hebei had a drying tendency and cities in Guangdong had a more humid tendency. Most cities in Hebei had a downward trend in extreme precipitation and an upward trend in extreme drought, while most cities in Guangdong had an upward trend in extreme precipitation and extreme drought. A flooding and drought evaluation system was constructed according to the climate change analysis of these cities, and the evaluation indicated that all cities of Guangdong had a high flooding risk and 28 cities (19.2%) of Hebei had a high drought risk. The 230 cities of the two provinces were divided into five types by use of the system, and stormwater management strategies were proposed for each type of city based on the LID strategy.

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